

RESEARCH ARTICLE

Heart rate variability and heart rate monitoring of nurses using PPG and ECG signals during working condition: A pilot study

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Abstract

The use of wearable photoplethysmography (PPG) technology for estimating heart rate (HR) and HR variability (HRV) in the health care system is gaining attention in recent years. However, the performance of these devices remains questionable in their ability to collect data in real working conditions for long-term monitoring. The present study aimed to examine the data collected from nurses during working hours by PPG and electrocardiography (ECG) devices. Twenty-two nurses underwent a 60-minute work protocol during the normal working conditions while wearing a PPG device and an ECG device. HR, low-frequency component (LF) and high-frequency component (HF), LF/HF ratio, and percent LF distribution in total spectral power, and steps were examined. Pearson's correlation analysis and Bland-Altman method was performed to examine the relationships between the two devices based on HR and HRV indices. The results found strong positive correlations between HR estimates of both devices, and moderate correlations between LF/HF ratio and percent LF indices estimates, respectively. Moreover, the Bland-Altman analysis showed a small mean bias in general between the captured data of both devices. This pilot study suggested that the PPG device appears to demonstrate good overall reliability in measuring HR, LF/HF ratio, and percent LF. A further large-scale study is required to investigate the feasibility and practicality for HR and HRV analysis in nurses during real working conditions using PPG devices.

KEYWORDS

heart rate, heart rate variability, photoplethysmography, stress tracking, wearable biosensors

1 | INTRODUCTION

Nursing is perceived as a strenuous job, in which nurses regularly suffered from serious musculoskeletal disorders and psychological disturbances, such as back pain and stress-related problems.¹ In particular, during the COVID-19 pandemic, nurses have experienced increasing

pressure, anxiety, exhaustion, isolation, and ongoing emotional trauma.^{2,3} The high level of workplace stress is becoming a major and serious problem for nurses, hospitals, and related institutions, and it significantly affects their quality of life, and the quality of care service they provide.⁴ Investigations have been conducted on workplace stress of nurses to identify their stressors, stress management intervention, and

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outcomes.^{1,5,6} Nevertheless, those studies mainly assessed the stress level of the subjects by questionnaires, and the examined activities were strongly tied to their perceived stress.⁷⁻⁹ If the activities could be tied to quantitative measures, it would provide a better grasp of the stress level of the nurses. Monitoring workplace stress for nurses objectively and efficiently, and providing proper intervention when necessary should be the main focus in making healthcare policy for nurses.

Heart rate (HR), blood pressure, and heart rate variability (HRV) are often regarded as physiological monitoring markers in stress assessment.¹⁰ In recent years, the quantitative analysis of HRV has been proposed as a possible way to study the effects of work-related stresses on cardiovascular autonomic regulation in high stress conditions.¹¹⁻¹³ HRV analysis was suggested to provide an objective measurement of stress in nurses group in theory.¹¹

Although electrocardiography (ECG) device can reliably measure HR and HRV signals,⁸ ECG electrode pad and chest strap often lead to skin irritation and discomfort at contact areas, especially on female subjects.^{9,14} Thus, it has been difficult to measure stress for a long period of time in real working conditions. As an emerging technology in recent years, photoplethysmography (PPG) wearable device is becoming a popular technology for continuous HR monitoring. Evidence showed that HR can be estimated reliably from the PPG method.^{15,16} Compared to an ECG device with an electrode pad and chest strap, PPG wrist-worn device is a more convenient and less intrusive measurement technique.¹⁵ Many smartwatches and wristbands contain PPG sensors, and their designs are getting more compact and user-friendly.⁹ However, these devices mainly provide HR measurement but not detailed HRV analysis. Most importantly, the performance of PPG sensors remains questionable with respect to data collection in actual working conditions due to motion artifacts.¹⁷

Getting accurate and detailed HRV measurements from PPG wearable devices remains a challenging problem. Even with the popularity and merit of PPG wearable devices, research work on the validation of PPG in HRV monitoring has not been thoroughly conducted.

Therefore, the present study aimed to investigate the data collected by a PPG device and an ECG device and to evaluate the PPG device's ability against the ECG device to accurately collect HR and HRV measurements for nurses under normal working conditions. In particular, the objectives of this pilot study are to analyze and compare: (a) the HR estimates; (b) LF/HF ratio estimates; and (c) percent LF estimates between the collected PPG and ECG signals.

2 | MATERIALS AND METHODS

2.1 | Participants

A convenience sampling method was used to recruit the participants. Inclusion criteria were as follows: registered nurse, on active duty, has no significant medical condition that may potentially influence HRV measurements, and is willing to volunteer to take part in this study. Twenty-two healthy nurses working at intensive care unit (ICU) and neurosurgery intensive care unit (neuro-ICU) at a public hospital in

Inner Mongolia Autonomous Region of China were finally selected in this study. The experiments were explained to each participant, and consent forms were signed beforehand. This study was approved by the ethics committee of the Affiliated Hospital of Inner Mongolia Medical University (No. KY [2019002]).

2.2 | Devices

2.2.1 | PPG device

The PPG device used in this study (SMARTEAP Stress tracker WSS-2, YiCheng Business Management & Consulting Co. Ltd, China) can be worn either on the wrist, lower, or upper arm. The device records data at 1-second interval using two LED sensors with a sampling rate at 25 Hz to achieve low-power consumption for long-time monitoring.¹⁸ In this study, the device was worn on the upper left arm, proximal part of the biceps brachii to minimize discomfort. Biological information, HR, low-frequency component (LF: 0.04-0.15 Hz), and high-frequency component (HF: 0.15-0.4 Hz) of HRV signal, were recorded during the experiment. LF is usually regarded as a marker of fluctuations in either sympathetic of sympathetic plus vagal activity, while HF is a marker of vagal activity.¹⁹ In this experiment, the following frequency domain parameters were analyzed: LF/HF ratio, and percent LF distribution in total spectral power (ie, $LF/[LF + HF]*100$). The spectral components were calculated as absolute units (ms^2).

2.2.2 | ECG device

The ECG device (myBeat-WHS-1, Union Tool Co. Ltd., Japan) was used to provide criterion measures of HR and HRV. The device was fixed to the chest around the epigastrium by a dedicated chest strap with electrodes. The ECG data were recorded at 1000 Hz. The HR, LF (0.04-0.15 Hz), HF (0.15-0.4 Hz), body surface temperature, and triaxial acceleration were recorded during the experiment. LF and HF components were calculated as normalized units (nu) with this ECG device. The HRV-based stress indices, LF/HF ratio, and percent LF, were also calculated. The detailed ECG processing and HRV analysis used in this device is explained in Ota et al.²⁰

2.3 | Procedure

The experiments were performed at a public hospital in the Inner Mongolia Autonomous Region of China. Information about the study was presented to the hospital management and the head nurses. Approval was obtained to conduct the experiment. The head nurses explained the main goals and relevant information of the experiment to the participating nurses. All participants signed the consent form and had the right to withdraw at any time. All personal information is protected according to the protocol approved by the ethics committee.

To compare the HR and HRV indices between PPG and ECG signals, all participants underwent a 60-minute work protocol during

normal working conditions while wearing a PPG device and an ECG device. In particular, the PPG device was worn on the upper arm, while the ECG device was fixed to the chest at the same time during the experiment. HR and HRV data were recorded concurrently and continuously throughout the experiment. One of the authors provided training on how to use the device to the nurses, retrieved the devices, and transferred the data to a computer after the experiment.

2.4 | Data collection and statistical analysis

The recorded PPG and ECG signals were retrieved using software provided by the manufacturers respectively. HR data were checked for integrity and then averaged at 1-minute intervals for analysis.²¹ The HRV parameters were analyzed in the frequency domain. Although the two devices use different units for LF and HF measurements, the HRV parameters being examined, LF/HF ratio, and percent LF are both ratios, so the difference in the unit does not influence the result. LF and HF were averaged at 5-minute intervals for further analysis.²²

Pearson correlation analysis was performed to determine the strength of the relationship between the two devices. Bland-Altman method was used on aggregate data of HR and stress values to assess the agreement between the two devices for HR and HRV measurements. Moreover, the PPG and ECG signals of the day and night shifts were further analyzed using Bland-Altman to assess the agreement more specifically due to the following considerations: (a) previous studies showed that shift schedule significantly affects the overall physical and mental health of nurses. Shift time is also often regarded as an influence factor of nurses' workplace stress.²³⁻²⁵ (b) The workloads in the day and night shifts were different in this experiment. It is possible that frequent arm movement may create motion artifacts in the PPG signals.²⁶ The Statistical Package for the Social Science was used for all statistical analysis.

2.5 | Tasks list during the experiment

The tasks and shifts of each participant can be found in the supplemental material.

3 | RESULTS

3.1 | The characteristic of subjects

In this pilot study, we enrolled 1 male and 21 females with an average age of 33.59 ± 4.93 years (body mass index [BMI] = 22.74 ± 3.25 kg/m²). Of them, 15 nurses (all females, mean age = 34.33 ± 4.10 years, BMI = 22.75 ± 2.61 kg/m², step/hour = 645.33 ± 190.27) worked in day shift, while 7 nurses (1 male and 6 females, mean age = 32.00 ± 6.45 years, BMI = 22.72 ± 4.59 kg/m², step/hour = 525.14 ± 217.33) worked in night shift. There was no significant difference in age, BMI, and steps between the two shifts. Analyzed PPG and ECG data were simultaneously collected from these 22 subjects. There were no missing data.

3.2 | HR estimates from PPG compared to ECG

The correlation coefficient, mean HR, and mean difference (bias) are presented in Table 1 and Figure 1. In the HR aggregate data ($n = 1283$), a strong positive correlation was found between the HR estimates obtained from both devices ($r = 0.974$, $P < .0001$). The degree of agreement between PPG and ECG methods was assessed using Bland-Altman analysis. The mean difference (bias) of HR aggregate data was found to be 0.493 ± 2.209 bpm (95% limit of agreement [LoA] 3.838, -4.823). A strong positive correlation was found in both day shift ($r = 0.975$, $P < .0001$) and night shift ($r = 0.970$, $P < .0001$). The PPG device demonstrated a mean bias of 0.398 ± 2.168 bpm (95% LoA 3.851, -4.648) for the day shift and 0.692 ± 2.284 bpm (95% LoA 3.785, -5.169) for the night shift (see Table 1).

3.3 | LF/HF estimates from PPG compared to ECG

Results of LF/HF data pair analyses were presented in Table 2 and Figure 2. The results showed that there was a moderate positive correlation for aggregate data, day and night shift data respectively ($r = 0.577$, $P < .0001$; $r = 0.617$, $P < .0001$, and $r = 0.464$, $P < .0001$). Compared to the ECG data, PPG data showed that mean scores were 0.153 ± 1.573 for aggregate data, 0.132 ± 1.532 for day shift and 0.198 ± 1.667 for

TABLE 1 Results for HR data

	Aggregate data ($n = 1283$)	Day shift AM 7:00 to PM 17:59 ($n = 871$)	Night shift PM 18:00 to AM 6:59 ($n = 412$)
PPG mean HR, bpm (\pm SD)	84.738 (9.675)	83.745 (9.711)	86.837 (9.265)
ECG mean HR, bpm (\pm SD)	85.230 (9.532)	84.144 (9.422)	87.528 (9.365)
Correlation (r) 95%CI	0.974***, 0.971-0.976	0.975***, 0.971-0.978	0.970***, 0.964-0.975
Mean bias, bpm (\pm SD)	0.493 (2.209)	0.398 (2.168)	0.692(2.284)
95% LoA (upper, lower)	3.838, -4.823	3.8508, -4.6475	3.785, -5.169
SD error of mean differences	0.062	0.073	0.113

Abbreviations: CI, confidence interval; ECG, electrocardiography; HR, heart rate; LoA, limits of agreement; n, per minute ECG and PPG data pairs; PPG, photoplethysmography; SD, standard deviation.

*** $P < .001$.

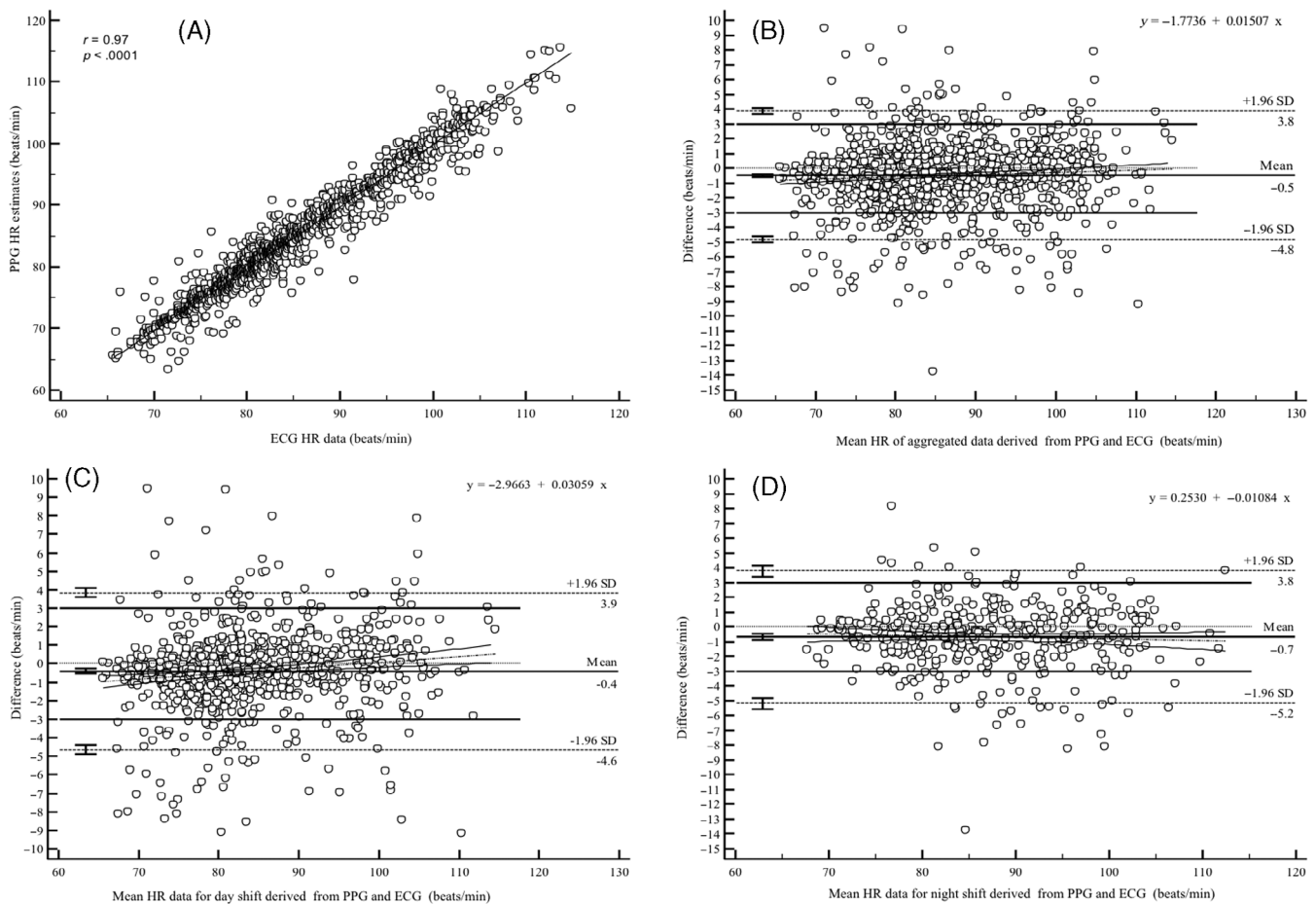


FIGURE 1 Results of HR estimates obtained using PPG and ECG. (A) The Pearson's correlation. Bland-Altman plots with bias and 95% limits of agreement for (B) aggregated, (C) day, and (D) night shifts HR estimates

TABLE 2 Results for LF/HF

	Aggregate data (n = 264)	Day shift AM 7:00 to PM 17:59 (n = 180)	Night shift PM 18:00 to AM 6:59 (n = 84)
PPG mean LF/HF (\pm SD)	3.557 (1.328)	3.374 (1.266)	3.954 (1.380)
ECG mean LF/HF (\pm SD)	3.404 (1.905)	3.242 (1.945)	3.756 (1.775)
Correlation (<i>r</i>) 95% CI	0.577***, 0.489-0.653	0.617***, 0.517-0.701	0.464***, 0.275-0.619
Mean bias, (\pm SD)	0.153 (1.573)	0.132 (1.532)	0.198 (1.668)
95% LoA (upper, lower)	3.235, -2.930	3.134, -2.870	3.466, -3.071
SE of mean differences	0.098	0.115	0.184

Abbreviations: CI, confidence interval; ECG, electrocardiography; HF, high frequency; LF, low frequency; LoA, limits of agreement; n, per 5-minute data pairs; PPG, photoplethysmography; SD, standard deviation.

*** $P < .001$.

night shift, respectively, and their corresponding 95% LoA were -2.930 to 3.235 , -2.870 to 3.134 , and -3.071 to 3.466 , respectively.

3.4 | Percent LF estimates from PPG compared to ECG

Table 3 depicts the mean, correlations coefficient, and mean bias in percent LF estimates obtained from the two devices. The Bland-

Altman plots for all data sets are shown in Figure 3. Similar to the result of the LF/HF estimates, moderate positive correlations were found between percent LF aggregate data ($r = 0.668$, $P < .0001$), dayshift data ($r = 0.685$, $P < .0001$), and night shift data ($r = 0.622$, $P < .0001$) obtained from the PPG and ECG devices. Moreover, the results of Bland-Altman analysis showed a mean bias of percent LF as 0.001 ± 0.069 (95% LoA 0.139 , -0.137) for aggregate data, 0.005 ± 0.068 (95% LoA 0.139 , -0.130) for day shift, and 0.014 ± 0.069 (95% LoA 0.122 , -0.150) for night shift. The high degree

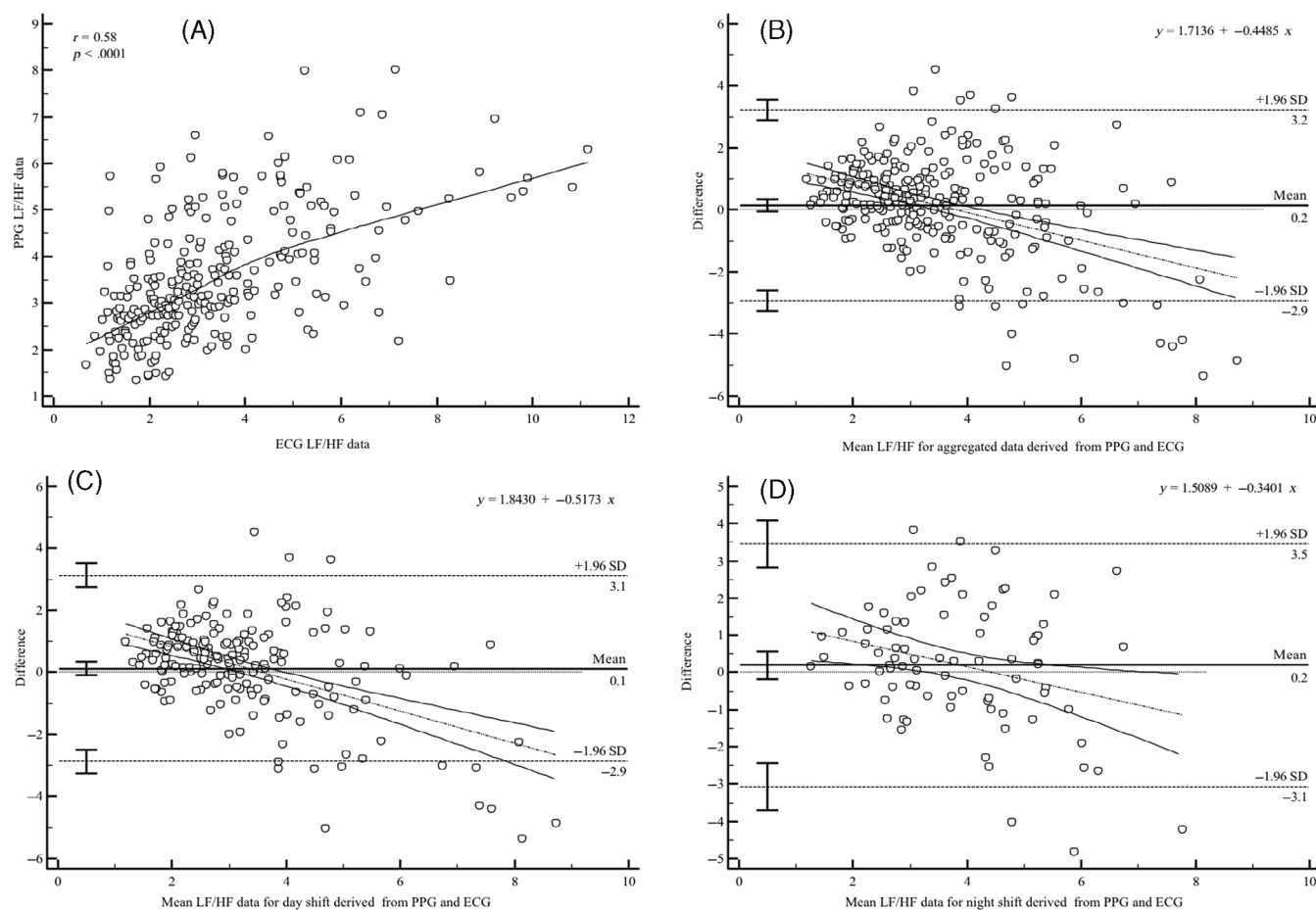


FIGURE 2 Results of LF/HF data pairs of PPG and ECG. (A) The Pearson's correlation. Bland-Altman plots with bias and 95% limits of agreement for (B) aggregated, (C) day, and (D) night shifts LF/HF estimates

TABLE 3 Results for percent LF

	Aggregate data (n = 264)	Day shift AM 7:00 to PM 17:59 (n = 180)	Night shift PM 18:00 to AM 6:59 (n = 84)
PPG mean LF/(LF + HF) (±SD)	0.709 (0.0701)	0.702 (0.067)	0.724 (0.075)
ECG mean LF/(LF + HF) (±SD)	0.711 (0.092)	0.698(0.094)	0.738 (0.084)
Correlation (r) 95% CI	0.668***, 0.595-0.730	0.685***, 0.596-0.754	0.622***, 0.471-0.738
Mean bias, (±SD)	0.001 (0.070)	0.005 (0.068)	0.014 (0.069)
95% LoA (upper, lower)	0.134, -0.137	0.139, -0.130	0.122, -0.150
SE of mean differences	0.004	0.005	0.008

Abbreviations: CI, confidence interval; ECG, electrocardiography; HF, high frequency; LF, low frequency; LoA, limits of agreement; n, per 5-minute data pairs; PPG, photoplethysmography; SD, standard deviation.

*** $P < .001$.

of agreement between the two methods was found for HRV parameters.

4 | DISCUSSION

This study examined the HR, LF/HF ratio, and percent LF measurements collected by PPG and ECG devices. The HR aggregate dataset

indicated a strong positive correlation and a very small mean bias between the captured data of the two types of devices. These findings agreed with previous laboratory studies,^{9,16} which reported similar correlations and a high degree of agreement of HR derived from PPG and ECG devices. The present study showed that HR measurements from the two devices used in this experiment are in a high degree of agreement for nurses under real working conditions. Considering the differences in workloads between shifts, we further

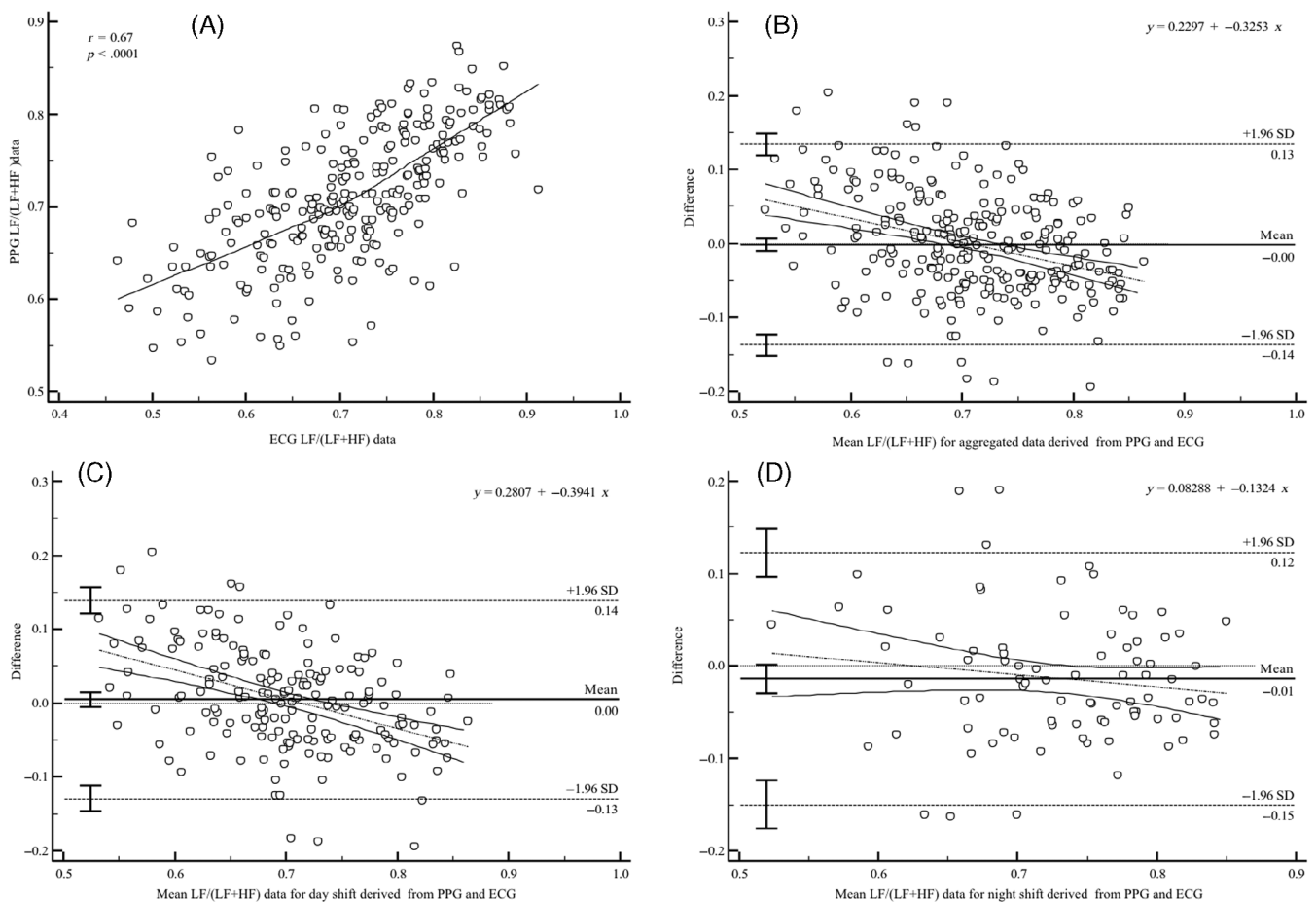


FIGURE 3 Results of percent LF data pairs of PPG and ECG. (A) The Pearson's correlation. Bland-Altman plots with bias and 95% limits of agreement for (B) aggregated, (C) day, and (D) night shifts percent LF estimates

analyzed the HR for day and night shifts respectively to examine the degree of agreement between PPG and ECG signal by the two devices more specifically. Similarly, in both shifts, the HR measurements obtained from the PPG device were strongly correlated to ECG measurements with a very small mean bias.

Both devices used power spectral density analysis to identify and remove the motion artifacts from the raw data to calculate the HRV parameters.^{9,27} The stress values are calculated based on HRV parameters from both devices. The LF/HF ratio and percent LF were used to assess the accuracy and reliability of the two devices. The result of the present study showed a moderate positive correlation between the two devices, and most of the mean bias pairs were within the LoA width. Overall, the results demonstrated that the PPG device achieved acceptable and comparable reliability as the ECG device in acquiring HRV parameters of nurses in real working conditions.

Since the PPG device was worn on the upper arm, feedbacks from the participants indicated that it did not cause any discomfort or interference in their movement. All participants preferred the PPG device over the ECG one. With the high level of agreement between the two devices shown in the results, this pilot study suggested that the PPG device is a feasible tool for collecting accurate HR and HRV parameters for nurses under real work condition.

There are several limitations to this pilot study. Firstly, the sample size is small which may affect the statistical power. Secondly, since some volunteers reported discomfort when wearing the ECG device after a long period of time in another previous study of ours, we decided to collect only 1 hour of data in this experiment. Moreover, only one model of PPG device and ECG device was used in the present study. More devices from different manufacturers should be used to examine the reliability of these devices in general in real working conditions in the future. Finally, HRV parameters can be affected by physiological factors (age, gender, day and night rhythm, and acute and chronic diseases)²⁸ and mechanical factors such as motion artifacts¹⁷ and sampling devices.^{18,22}

Overall, in conjunction with existing self-evaluation mechanisms, PPG wearable devices that are capable of collecting HRV parameters in real working conditions will contribute to the stress management of nurses to reliably assess their conditions, and to evaluate the effectiveness of interventions.

5 | CONCLUSIONS

In this study, we examined the validity of the HR and HRV parameters measurements captured by a PPG device and an ECG device

from nurses during normal work conditions. Our results showed that the PPG device was able to show reliable HR and HRV parameters at a level comparable to the ECG device. Since nurses are faced with excessive levels of workplace stress, in addition to subjective self-evaluation questionnaires, it is beneficial to regularly collect objective data such as HR and HRV parameters to rapidly detect fluctuations in the stress levels in nurses and to provide early interventions accordingly. Our pilot study demonstrated the feasibility of using wearable PPG and ECG devices to perform short-term monitoring. In the future, large-scale long-term studies with larger study populations should be conducted to further evaluate the reliability of PPG and ECG devices in monitoring the work conditions of nurses.

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CONFLICT OF INTEREST

The authors declare no conflicts of interest.

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Writing—Review and Editing: Xinxia Li, Chenghong Hu.

All authors have read and agreed to the published version of the manuscript.

Chenghong Hu had full access to all of the data in the study and takes complete responsibility for the integrity of the data and the accuracy of the data analysis.

TRANSPARENCY STATEMENT

Xinxia Li affirms that this manuscript is an honest, accurate, and transparent account of the study being reported; that no important aspects of the study have been omitted; and that any discrepancies from the study as planned (and, if relevant registered) have been explained.

DATA AVAILABILITY STATEMENT

The data supporting the findings of the present study will be available on request to the corresponding author.

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SUPPORTING INFORMATION

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